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Analysis of information interdependencies between product development and manufacturing system planning in early design phases

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Abstract

Manufacturing system planning (MSP) and product development (PD) are two highly interdependent domains of the product engineering process (PEP). Product design decisions impact on tasks and alternative solutions of the corresponding manufacturing system and vice versa. According to the “rule of 10” in quality management, especially within early design phases decisions highly impact on the accuracy of the overall result. Even today, PD and MSP are commonly processed sequentially without integration or interlinkage between the two domains. Existing integrative approaches aren’t successfully implemented in most companies.
An innovative approach for integrating PD steps and tasks of MSP aims at an early conceptual design of the manufacturing system. While within PD, a conceptual view on the product exists, within MSP no early conceptual design is performed. Thus, a conceptual design for manufacturing systems is needed for a better integration of the two domains. In this context an integration of the process phases specification and concept design from PD together with preparation and structure planning from MSP is auspicious. For the integration of these early phases some preliminary analyses have to be performed.
This paper presents the results of the interdependencies and information exchange analysis between PD and MSP in the phases named above. The information content is outlined and an approach for the information classification is given. The information is distinguished by the way it is used within the two domains and conclusions from the analysis are drawn for the concept to develop.

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Keywords: Planning; Integration; Manufacturing; Product; Development.

1. Introduction

Manufacturing companies are permanently confronted with the challenge to reduce the duration of the product engineering process (PEP), aiming at a shorter time-to-market [1] for new products and an earlier start of production [2]. This persistent challenge exists almost as long as the manufacturing industry itself and is triggered by changing circumstances like technological progress and social evolutions. Recent examples are an intensifying market saturation and changing customer demands for individualized products manufactured at the same costs as mass products [3]. To meet the demands and maintain own competitiveness, companies have to handle increasing complexity [4, 5] and product variety [6], technologies and business models. Shortened product life cycles, caused by changing customer demands or by shortening technology life cycles, enforce according product changes. Consequently, the frequency of product developments increases. Therefore, even more flexibility in organization, planning and manufacturing is necessary [7]. To meet the challenge of the need for an even shorter PEP, product development (PD) and manufacturing system planning (MSP) have to be processed faster and process phases of the two domains have to be integrated and parallelized further. None of these objectives are truly new. Approaches like simultaneous engineering originating from the 1980s [8] or developments linked to the digital factory [9] already had the same objectives. But still, the processes of PD and MSP, defined as two sequent parts of the PEP, neither reached a considerable parallelization nor integration [10].

In this paper, an innovative approach to integrate the two domains is presented. It especially focuses the early phases of the development processes of PD and MSP (Fig.1) and aims at

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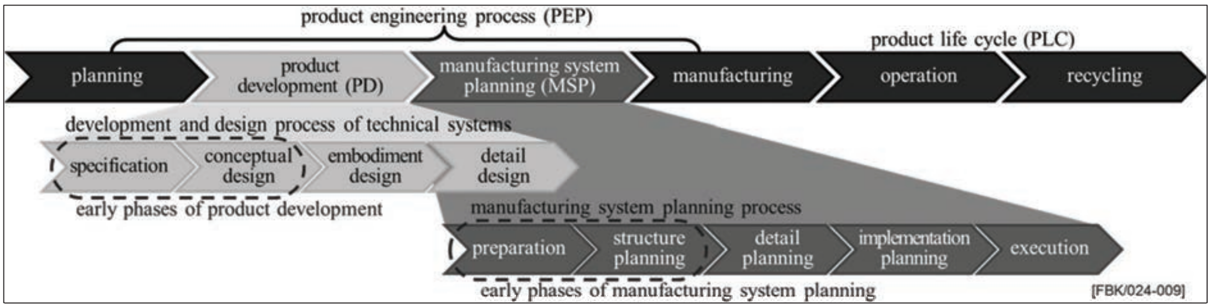


Fig. 1. Definition of early phases of product development and manufacturing systems planning within the product engineering process

integrating process steps and parallelizing process phases. Therefore, in the following, the PEP is elucidated. It is defined, which phases are considered "early" and their contents are outlined. Thereafter, the intended approach is described with objectives and development tasks. One of them is the analysis of information interdependencies between PD and MSP in early design phases. A classification of this information as well as an overview over the results of the analysis is given.

2. Early phases within product engineering process

In the following, the sequential PEP and the early phases of PD and MSP are defined and outlined. Furthermore, existing approaches for integrating PD and MSP are presented.

2.1. Sequential product engineering process

The product life begins with the first product idea. It initiates the product lifecycle (PLC), which contains the PEP. Most commonly, the PEP is defined by three sequential phases, but not invariably the same ones. As shown in Fig.1, in one case, planning is included but manufacturing is not [11] and vice versa [12]. However, PD and MSP are always part of the PEP.

The domains of PD and MSP both use process models with sequentially performed process phases to structure their tasks. Within PD four process phases are mostly agreed on (Fig.1). They are recorded by VDI guidelines 2221 [12] and 2222 [13] and based on, inter alia, methods of Pahl/Beitz [14], Hubka [15] and Rodenacker [16]. Apart from the sequential process models some other approaches for PD exist, e. g. the Munich Product Concretization Model [17] or the approach for PD of Ulrich and Eppinger [18]. MSP literature also defines a range of classical process models e. g. by Kettner [19], Grundig [20], Wiendahl & Nyhuis [21] Schenk [22] or Bellgran [23]. These classical process models differ with respect to the number of phases, to the level of detail, or the start and end point. But all models equal with regard to the contents and the analytical procedure. For harmonization, the contents of all classical models can be allocated to five reference phases (Fig.1) [24]. In addition, several newer ones exist like the manufacturing system design by Suh et al. [25], the counterflow method of factory planning [24] or Aachen's factory planning approach [26]. They can cope with some of the classical ones' disadvantages, but at the core, they are based upon them.

This paper focuses the early phases of PD and MSP. The definition of "early" is shown by Fig.1, including specification and conceptual design phase from PD and preparation as well as structure planning phase from MSP. In the following, the contents of these early phases are outlined in detail.

2.1.1. Early phases of product development

The process of PD begins with the specification phase. It aims at clarifying and specifying the development task, which is given either by the customer or the product planning. All available information on the product is collected, the design specification is formulated and documented in a requirements list. It serves as input to the conceptual design phase [12].

The conceptual design phase develops the product concept within several design stages [1]. It represents the principle solution of the product [14]. The first design stage investigates all collected information to determine the main purpose of the product, which defines the primary function of the product. Besides often additional purposes exist, which are represented by secondary functions. All functions are broken down into sub-functions and structured within a hierarchy of functions. Here, the connections between functions and their inputs and outputs are represented by flows of energy, material or signals. The first design stage results in the function structure of the product [12]. Based on this, the next design stage determines possible working principles for each sub function. Working principles are defined by a physical effect, material characteristics and geometric specifications or restrictions [15]. The gathered set of working principles is used to combine alternative variants of working structures. Each variant possesses other characteristics, advantages or disadvantages, depending on the degree of synergetic interaction of the working principles contained [16]. However, the combination of the best-fitting working principles of each sub-function does not inevitably lead to the best working structure. By using common selection and evaluation methods, different working structures have to be balanced against each other to achieve the ideal principle solution for the product [14]. Here, it is important to notice, that the same function structure can be fulfilled by many different working structures and the optimum choice of working structure is a multicriteria decision problem.

2.1.2. Early phases of manufacturing system planning

The first phase of MSP is the preparation and contains the tasks of objectives planning and preliminary work. Because MSP objectives are derived from strategic corporate objectives, the corporate management is responsible for objectives planning [19]. Beginning with the initiation of the planning process, planning tasks and the current situation are analyzed and initial ideas are collected. Based on this, a first theoretical draft of the problem solution is worked out. It serves for the estimation of scope, consequences and capital expenditure. Thus, highly complex tasks have to be executed strongly abstracted at a very early stage within the planning process [20]. Preliminary work serves the purpose of analyzing available capabilities in case of already existing manufacturing systems. In addition, based on management objectives the production program is determined. It is highly influential on the future capabilities and structure of the manufacturing systems, since it determines the product range, types, variants, and quantities to manufacture [22]. As shown by the law of inversion in factory planning, MSP is determined by its output [27]. Hence, at the beginning and during the early phases of MSP the product's specification, constructive & technological design or production program are fuzzy [1], incomplete and changing [23]. Regardless, preliminary decisions for solution alternatives of the manufacturing system have to be made, e. g. on type of production, production principle or logistics concept for a timely consideration of a flow-suitable layout. Furthermore, based on the production program, the need for technologies, machines or staff is calculated or estimated, depending on the accuracy of the available information [22].

The structure planning phase is divided into two separate tasks, which build upon each other: the ideal planning and the real planning. The objective of the phase is to design a rough ideal layout for the manufacturing system and several solution variants for the real layout. Within ideal planning a synthesis of functions, dimensions and structure is executed independent from real conditions [19]. Necessary technologies, equipment and their functional and processual dependencies are analyzed and the quantitative needs for area, equipment and staff are calculated. The outcome of ideal planning is a functionally, technically and organizationally appropriate arrangement and linkage of all required manufacturing system elements. Based on this, real planning additionally considers existing spatial circumstances and therefore develops different real layout variants based on the ideal layout [20]. The preferred variant for further detailing is chosen by weighting the pros and cons, the fulfilment of the requirements, the performance and the cost-benefit-ratio of different real layout variants [21]. Considering the foregoing, structure planning represents the innovative core task of MSP due to the fact that the fundamental solution of the manufacturing system is negotiated within this phase.

2.2. Existing integration approaches for PD and MSP

Already, several approaches rose to the challenge of advancing and accelerating the PEP. Sequential planning processes were criticized early because of their inefficiency, lack of interlinkage and unsuitability for collaborative work [28]. Already in the 1980s the idea of simultaneous resp. concurrent engineering (SE) was developed [29]. Its objectives are the shortening of development times, the lowering of change costs, the increase of quality and a smooth ramp-up, achieved by a parallelization of processes within companies [30]. Several integration approaches were developed based on the idea of SE. Examples are the concept of integrated design of products and processes by Eversheim [31], the design methodology for mechatronic systems by VDI guideline 2206 [32], the 3-cycle-model of product engineering [33] or the integrated product and manufacturing design by Britton et al. [34]. All previous approaches provide promising ideas but none of them were able to become industrially established. Reasons are e. g. a high communication effort associated with SE, a mere integration of PD and MSP during late development phases or a lack of profound procedures and methods. Thus far, no approach aims at detailed analysis of early design phases to develop a method for the integration of PD and MSP.

3. Early manufacturing system concept

According to the foregoing, an innovative approach is needed to integrate PD and MSP to achieve the objectives mentioned above. In the following, such an approach is presented with its purpose, objectives and necessary steps for its development.

3.1. Purpose and objectives of the approach

Existing integration approaches for PD and MSP mostly use information from later phases of the PEP. E. g. they connect a product's CAD-model with technologies used within the manufacturing system. In this paper, an approach for connecting information from early development phases of PD and MSP is focused according to the definition given above. Its purpose is to provide information on the manufacturing system at an earlier time than it is available so far and in a more structured way, inspired by the way the product is described in conceptual design phase [1]. Hence, earlier interaction, more frequent information exchange and better mutual coordination between the two domains of PD and MSP is facilitated. This is possible due to recent developments in the field of formal description languages. They enable to handle a higher degree of complexity.

The objective of this approach is to develop an early manufacturing system concept inspired by the product concept developed within conceptual design (Fig.4). The manufacturing system concept is supposed to provide initial information e. g. restrictions, specifications, detected conflicts of goals between product design and manufacturability, structures, technological preferences or system elements at a high level of abstraction. This information influences the design and elaboration phase of the product. Before, product developers have not received this kind of production-related decision making assistance. This leads to manufacturable products with anticipated lower costs, higher quality and a smoother production ramp-up.

3.2. Steps for the concept development

For the concept development, five main tasks have been spotted yet and are illustrated in Fig.2. The first one covers the analysis of existing approaches and process models for PD, MSP and integrative approaches. Thereby a special emphasis is placed on the closed set of information needed and provided within early phases as well as advantages, disadvantages and best practices of given integrative approaches.

The second main task deals with the information overlap and dependencies within early design phases of PD and MSP. The state of the art for dependencies is analyzed and possibilities for information exchange are deduced, which have not been used so far. Therefore, the closed set of information (first main task) is analyzed based on the criterion of information utilization within PD and MSP. The results of this analysis are outlined in chapter four of this paper.

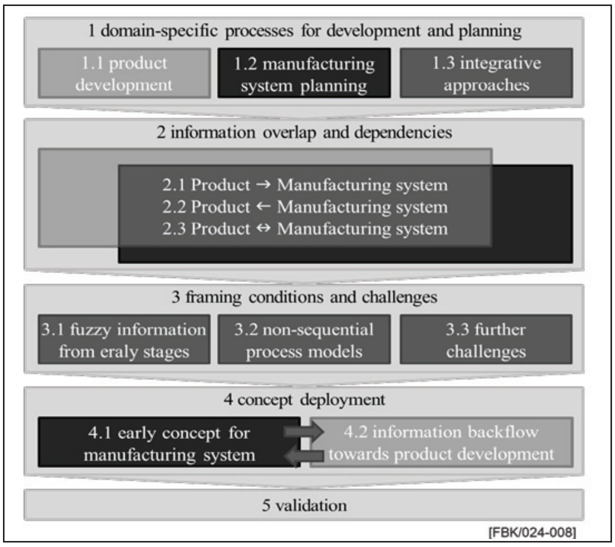


Fig. 2. Steps for the concept development

The utilization of information from early process phases causes special framing conditions and challenges. These are e. g. the handling of information fuzziness [1] and the thereby induced complexity [4] or the search for non-sequential process models, which better meet the requirements of the aimed frequent information exchange and coordination between PD and MSP. These challenges are addressed within the third task.

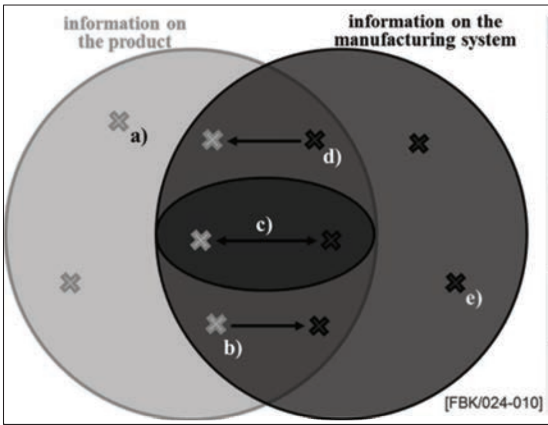
The fourth main task constitutes the actual development of the manufacturing system concept. It builds on the foundations provided by the pervious tasks. First, the manufacturing system concept must be worked out including contents, structure and process model. Then, an approach for information exchange and cooperation between PD and MSP has to be developed based on the contents of the concept. Together, the approach is thought to be both more efficient and less complex than other known approaches. Thereafter, a validation is needed to substantiate the effectiveness of the developed concept.

4. Analysis of information interdependencies

To analyze the information interdependencies between PD and MSP, it is important to know which information is exchanged between PD and MSP and how this information is used by the two domains. Therefore in the following a criterion for the classification of this information is suggested and the results of the analysis based on the criterion are presented. Last, conclusions for the further concept development are drawn from the analysis.

4.1. Criterion for information classification

Within specification and conceptual phase as well as preparation and structure planning a closed set of information is required, processed and generated. This information can be classified by its utilization within the two domains. Five different classes can be distinguished, which are illustrated by Fig.3. The figure shows two circles, representing the two sets of information describing the product and the corresponding manufacturing system. The intersection of the two circles represents all information from one domain, which is influential to the other one. Information beyond the intersection (class a) and e)) is only used by and influential to the domain which creates it. Therefore, these classes are not relevant for the further concept development. An example for class a) are the product functions. The same functions can be realized by many different product designs. Thus, this information is irrelevant for MSP. Three different classes can be distinguished within the intersection. The classes b) and d) contain information, which is generated by one domain and is used as input to the other. The fifth class is formed by the intersection of class b) and d) and is the most important one. It represents the subset, where information from PD and MSP directly



	Class	Example
a)	process-internal information from PD, only concerning the product itself	PD: The main functions of the product are cooling and heating.
b)	information on the product influencing the manufacturing system (input to MSP)	PD: Functional surfaces must be harder than normal surfaces. → MSP: A process for hardeness increase is needed.
c)	information on the product and the manufacturing system, which directly depend on each other (interaction necessary)	Variants for part design (PD) lead to alternitive manufaturing technologies (MSP) → decision making due to mutual consideration and cooperation
d)	information on the manu-facturing system influencing the product (input to PD)	MSP: The manufacturing task is mass production → PD: Metal housings must be construted cast-suitable instead of welding-suitable
e)	process-internal information from MSP, only concerning the manufacturing system itself	MSP: Within logistics planning overhead conveyer must be prefered to automated guided vehicles (AGV).

Fig. 3. Classification of information flows between PD and MSP by their utilization within the two disciplines including examples

depend on each other, necessitating a close cooperation and coordination between the two domains. Fig.3 registers one example for each class while taking into account that the examples are not merely from early phases, but from the whole PEP and just intend to illustrate and clarify the different classes.

4.2. Results of the analysis in information utilization

The following paragraph provides an overview of the results of the analysis and indicates some conclusion drawn from these results. Fig. 4 shows an illustration of the recognized information exchanges between PD and MSP in general (below) and with special emphasis on the early phases (above). Solid line arrows represent actually occurring information exchanges. Broken line arrows represent the intended information exchanges that must be developed by the concept.

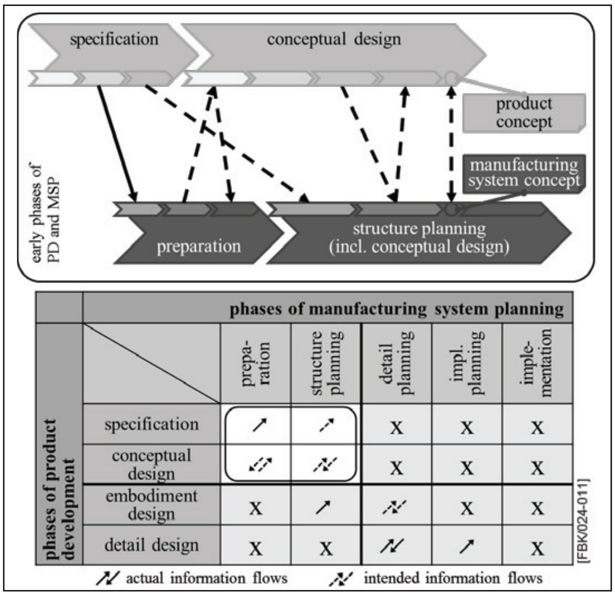


Fig. 4. Actual and intended information flows between PD and MSP

4.2.1. Information inputs from PD to MSP

Every MSP process begins with the task of production program planning. Information from PD is needed regarding product types to manufacture with their quantities, temporal reference periods and intended manufacturing costs in order to define the operating capability of the manufacturing system. This information determines the most economic production type (single-unit, series or mass production), the stocking strategy (engineer-to-order, make-to-order or make-to-stock) and the most efficient production principle (flow, island, job shop or fixed-site production), predetermining functions, dimensions and structures of the manufacturing system [20].

At the end of conceptual design respective at the beginning of embodiment design, the product architecture is defined by PD. It specifies the main functions, the vital features, the module structure and the future variability of the product. It also determines the transition point from low-cost mass production of standard parts to expensive customized parts for product individualization. Thereby, it hugely influences the unit costs within manufacturing. In collaboration with the controlling department, make-or-buy decision for modules, subassemblies and parts are made by PD. These decisions are based on the product architecture and are made at a time when MSP often has not even begun. Still, these decisions influence the organization of responsible divisions for MSP [14].

The product architecture is also used to derive the product structure. While the module structure strongly influences the assembly sequence of the product and the material flows, the product structure defines the configuration point for customer-neutral parts manufacture. Thereby, it indirectly specifies the division between pre- and final assembly [12].

Depending on the PD case (new, customized, variant, repeated design) the product architecture also decides on the usage of already existing modules, parts or product families. By adopting the product structure of previous products, MSP is enabled to further utilize existing resources and similar sequences for manufacturing and assembly. Besides this, the choice of construction (e. g. integral or differential) influences the flexibility of manufacturing and assembly sequences [15].

Tolerances specified by PD are accuracy requirements for manufacturing or assembly processes and therefore influence the selection of processes, its complexity and costs [13].

4.2.2. Information inputs from MSP to PD

At the beginning of PD, product requirements from different stakeholders including the manufacturing system are collected. Since MSP has not been started yet, these requirements often originate from experiences with previous manufacturing systems [14]. Therefore, PD also uses design guidelines for manufacturing- or assembly-suitable products. Additionally, some companies own internal guidelines for design engineers. Hence, there is no case-specific information flow from MSP to PD, but generalized information and best practices concerning the manufacturing system [13]. In this context, PD aims at the best trade-off between product requirements, simple processes, low resource expenses and faultless ramp-up. Thus, in early PD phases, the challenge of MSP-suitable design is to provide detailed requirements for operational processes [22].

PD has to consider existing technologies, processes, machines and resources depending on the MSP case (green-field, change, expansion planning). Within a company, the commitment to technologies or special machines is already registered within the requirements list [19]. The conceptual design needs this information to sort out product concept variants, which do not fit the requirements of the existing manufacturing circumstances [35]. The embodiment design has to note the design restrictions, which are associated with existing machines or technical equipment. This is economically reasonable, though it may lead to a technically unoptimized product design [14]. Within embodiment design phase, the product architecture is optimized with regard to the assembly. Here information from the manufacturing system, especially from the assembly system design, is needed [15].

4.2.3. Interdependent information from PD and MSP

Within early phases, interactions between PD and MSP hardly occur. One example is the first choice of processes and process chains leading to the applied equipment, which is based on the product architecture and coordinated with PD. Thereby, MSP assumes fixed specifications regarding qualities and output quantities as well as the requirement for manufacturing at optimal costs [14].

Another example is the dependency between product architecture and plant engineering in terms of dimensions, number of assembly stations and transport technology or the dependency between joining techniques and joining processes in terms of automation capability, cycle time or process costs [20]. At a later time within the process, the chosen geometry for parts or modules determines the means for feed, storage, separation and transport and therefore has to be negotiated with the MSP [21].

4.3. Conclusions to the results of the analysis

Today, direct interrelation between PD and MSP seldom occur within early phases. Here, new connection points between the two domains have to be developed.

The most important aspects of PD within the early design phases are the functions, the working principles of the product and the first product architecture. These three aspects conclude the product concept. None of these aspects are taken into account within the early phases of MSP.

Product functions are mostly independent from special physical realizations and therefore do not provide a starting point for the intended conceptual design for manufacturing systems. However, working principles are defined by a physical effect as well as geometric and material specifications. Thus, on a high level of abstraction, they provide a first starting point for the conceptual design of the manufacturing system. The product architecture also constitutes a promising point for interactions between PD and MSP. Consequently, these aspects have to be investigated in more detail.

5. Summary and Outlook

This paper provides an approach for a manufacturing system concept based merely on information from early PD. Early PD phases are defined, contents are outlined and information dependencies between early phases of PD and MSP are analyzed. The information is classified by its use within the two domains. Conclusions are, that early conceptual aspects like working principles or the product architecture are not yet used for the early concept of the corresponding manufacturing system. Thus, further research should aim at the connection between these aspects and the tasks of early MSP phases for a deeper integration of the two design domains.

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